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First Broadband Results with a VLBI2010 System

Arthur Niell [1], *Wendy Avelar* [2], *Christopher Beaudoin* [1], *Roger Cappallo* [1], *Tom Clark* [4], *Brian Corey* [1], *Irv Diegel* [5], *Mark Evangelista* [5], *Ricky Figueroa* [2], *Skip Gordon* [5], *Ed Himwich* [4], *Chuck Kodak* [2], *Chopo Ma* [3], *Russ McWhirter* [1], *Katie Pazamickas* [2], *Mike Poirier* [1], *Jay Redmond* [5], *Alan Rogers* [1], *Chester Ruszczyk* [1], *Dan Smythe* [1], *Jason SooHoo* [1], *Mike Titus* [1], *Bruce Whittier* [1]

1) *MIT Haystack Observatory*
2) *ITT Corp.*
3) *NASA/Goddard Space Flight Center*
4) *NVI Inc.*
5) *Honeywell Technology Solutions, Inc.*

Contact author: Arthur Niell, e-mail: aniell@haystack.mit.edu

Abstract

The next generation geodetic VLBI instrument is being developed with a goal of 1 mm position uncertainty in twenty-four hours. The broadband signal chain, which is essential for obtaining the required delay accuracy from a network of relatively small antennas, has been implemented on the 12-meter antenna at the Goddard Space Flight Center, Maryland, USA, and on the 18-meter Westford antenna at Haystack Observatory, Massachusetts, USA. Data have been obtained in four 512 MHz bands spanning the range 3.2 to 9.9 GHz using commercially available broadband feeds, LNAs, digital back ends, and recorders. The first geodetic-style observing session has been completed. While demonstrating that the broadband hardware functions as expected, the six-hour session has illuminated areas of the scheduling, correlation, and post-correlation process that require improvement.

1. The VLBI2010 Broadband Observing System

The potential of the broadband delay and some of the expected challenges in processing the data were presented in the report on the Proof-of-Concept (PofC) system in the Proceedings for the previous IVS General Meeting [1]. Since that time a fundamental element of the VLBI2010 concept, a fast-slewing 12-meter antenna [Figure 1], has been installed adjacent to the 5-meter antenna at the Goddard Geophysical and Astronomical Observatory (GGAO) on the grounds of the Goddard Space Flight Center, and the PofC instrumentation has been replaced with production versions of the broadband signal chain. The principal replaced components are the feed, digital back end, and recorder, each of which are described in the following paragraphs.

A significant improvement to the VLBI2010 system is the incorporation of the quadruple-ridged flared horn (QRFH) feed in place of the Lindgren feed that was used for the PofC demonstration. The QRFH feed was developed at Caltech [2] and provides the two desirable features for geodetic VLBI, beamwidth and phase center that are largely independent of frequency over the 2-14 GHz range. Equally important, this is achieved using only one low noise amplifier (LNA) per polarization. As with all proposed feeds, the QRFH output is dual linear polarizations. Different versions of the QRFH feed are used for the two antennas due to the different f/D ratios.

The digital back end, designated RDBE-H (hereafter referred to as RDBE), is a completely new design developed by NRAO-Socorro and MIT Haystack Observatory [3]. Features new to the

Figure 1. The MIT 12-m antenna installed at Goddard Space Flight Center. This is the first antenna fully configured for VLBI2010 operation.

RDBE compared to the DBE1 used previously are selectable channel output, improved threshold setting for quantization, adjustable attenuators for setting power levels on input, and control and synchronous detection of an external noise diode for measurement of system temperature. The output of the RDBE is via 10 Gigabit Ethernet in Mark 5B format for recording on the Mark 5C.

Conversion of the RF signal to IF is accomplished by the UpDown Converter, a component used in the PofC that did not require any improvement.

Another step in the move to VLBI2010 is the use of the DiFX software correlator [4]. This has required the addition of the capability of converting the native output into Mark IV format, which has been accomplished by the creation of a program *difx2mark4*, which parallels *difx2fits* for conversion to the astronomical data format.

A basic assumption in the broadband concept is that the data from the four bands and both linear polarizations will be fit coherently for the delay observable and for the differential ionosphere dispersion. This, and the use of all available phasecal tones in a channel, have required significant modifications and additions to the estimation program *fourfit*.

The broadband concept is that data from four bands spanning approximately 2.2 GHz to up to 14 GHz will provide sufficient phase accuracy to estimate the VLBI delay and differential ionosphere with no ambiguity. Thus a total of four parallel hardware paths are required. The signal chain that has been designed to implement this concept is shown in Figure 2.

2. The Observations

In order to obtain data to evaluate how well the complete VLBI2010 system, from antenna through analysis, is functioning, a six-hour geodetic-style observing session was carried out on 2012 May 16. The different components of the test were a) preparing the observation schedule; b) observations; c) correlation; d) post-correlation estimation of the observables; and e) estimation of geodetic and instrumental parameters using *calc/solve*.

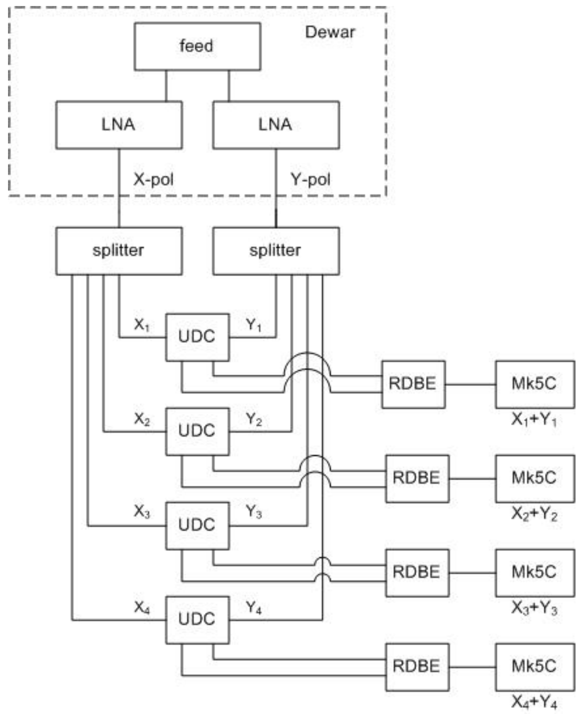

Figure 2. Diagram of the Broadband Delay system hardware. The dashed line indicates the components that are mounted on the antenna and cooled to approximately 20K. Phase and noise calibration signals are injected between the feed and each LNA. X-pol and Y-pol represent the two linear polarization signals produced by the QRFH feed.

a. Scheduling

Decisions to be made for scheduling include the observing "frequence" (frequency sequence) for the bands, the channel distribution within a band, minimum or maximum integration time per source, minimum SNR, and the set of sources.

Based on the System Equivalent Flux Density (SEFD) measured for each antenna from 3 GHz to 12 GHz, the frequency range was chosen to be 3.2 GHz to approximately 9.9 GHz. Bill Petrachenko calculated the locations of the 512 MHz bands that require the minimum SNR to resolve phase, and he derived a sequence with lower-band-edge frequencies of 3248.4 MHz, 5296.4 MHz, 6320.4 MHz, and 9392.4 MHz. The odd 32 MHz channels from the polyphase filter bank (PFB) output of each band were recorded for a total rate of 1 Gbps for each band-polarization.

The sequence of sources observed was generated by *sked* in *auto-sked* mode.

In order to ensure a minimum SNR of approximately 15 per band per polarization for all sources, the minimum scan time was set to 30 seconds. This also allowed for some variation in the SEFDs, which was important given the lack of knowledge of the variation of SEFD with azimuth and elevation for each antenna. In addition to this restriction the maximum duration of a scan was set to 60 seconds. As scheduled, no scan was more than 30 seconds in duration.

The geometric horizon mask was used at both antennas, but no mask was applied to restrict observations in the direction of the two Satellite Laser Ranging (SLR) systems (see next section). The schedule produced by *sked* contained approximately 30 scans per hour.

b. Observing

The six-hour session began 2012 May 16 at 1400 UT. The two SLR systems at GGAO were in operation so the aircraft-avoidance radars were transmitting at 9.4 GHz. In order to avoid possible damage to the VLBI amplifiers, the 12-meter was restricted from pointing within a 40° cone in the direction of the SLR systems, resulting in the loss of approximately 20% of the scheduled observations. Studies are under way to mitigate the power from the radars as seen by the VLBI antenna, but until such capability is implemented, the sector of the sky in the south (at GGAO) will have to be avoided when the SLRs are operating.

c. Correlation

The DiFX correlator at Haystack Observatory was used to correlate all four cross-polarization products simultaneously for each observation. All available phase cal tones from each channel were used to form a delay which was then applied to that channel. This is convenient with the DiFX correlator since all tones can be extracted simultaneously with the cross-correlation.

d. Post-correlation Analysis

Estimation of the observables, e.g., delay, rate, and amplitude, from the four bands requires that the correlator outputs of the four separate correlations be merged. A coherent fit to the data from the four polarization cross-products for all four bands is made for these three observables and for the difference in line-of-sight ionosphere TECs for the two sites. A sample of the residual phases for one scan is shown in Figure 3.

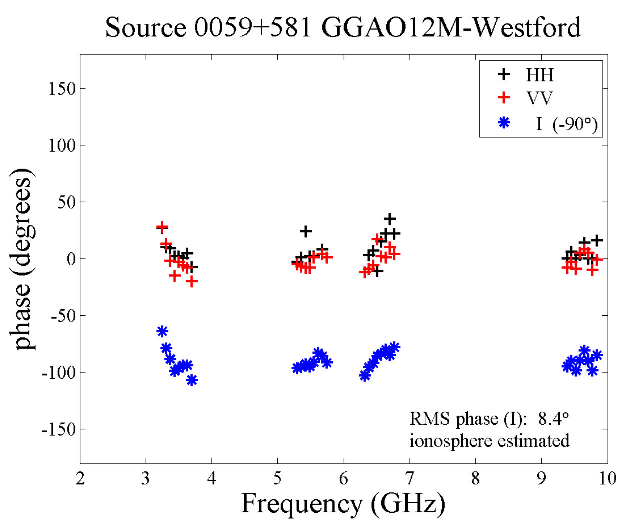

Figure 3. Residual phases after estimation of delay, rate, amplitude, and differential ionosphere for each of HH, VV, and I (combined) polarizations.

e. Geodetic Parameter Estimation

The resulting broadband delays were used to obtain a preliminary estimate of the vector baseline between the two antennas. While the formal delay uncertainties are of the order of only 1 picosecond, a realistic precision is about three to four times that, based on the RMS scatter of the phases among the 32 channels. However, the RMS post-fit residual of about 10 picoseconds is most likely due to incomplete modeling of the atmosphere and clocks in this preliminary solution.

The piecewise linear clock differences and atmosphere zenith delays were at 20 minute intervals. No gradients were estimated. The position uncertainties for GGAO12M, assuming Westford fixed, are 9 mm and 2 mm in the vertical and horizontal components, respectively, from the 106 accepted observations. In addition to the 20% lost due to the mask for the SLR radar, another 39 scans were not usable in the current analysis because of low amplitudes in the highest frequency band. This is expected to be corrected, which will allow their inclusion of the observations in a later analysis.

3. Discussion

These results show that the antenna, broadband instrumentation, correlator, post-correlation processing, and geodetic parameter estimation programs all are functioning as expected. However, there are several subsystems that either have not been completed or have not been tested, such as the Monitor and Control Infrastructure and the noise calibration control. Other areas needing upgrading are *sked* and the Field System. The Mark 6 recorder should be available for testing in a few months. Field System control of the Mark 6 recorder must also be implemented before it can be fully incorporated.

Finally, coordination of observing with the SLR systems is critically important in order to avoid losing the geometric strength that arises from observations in the southern sky.

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